The Franck-Hertz experiment re-considered

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Abstract

The celebrated Franck-Hertz experiment is reinterpreted by analogy with the *Glimmentladung* experiment, formerly performed by Heinrich Hertz.

Introduction

The experiment of James Franck and Gustav Hertz in 1913 is considered crucial in quantum theory. In facts, it is said to bring evidence of the existence of discrete energy levels in the matter in the gas state. In 1949, Heisenberg still deemed it a fundamental experiment [1]. However, that experiment and its successive improvements have been interpreted in the framework of the atomic model by Bohr and Sommerfeld. Those models definitively fell on the anomalous Zeeman effect, which the Heisenberg theory explained. At this point, we address to this specific issue a question that Schrödinger put in general [2]: *Do we mean this experiment to validate the* Kopenhagener Geist *of quantum theory or else do we just admit that the interpretation of its experimental result is surviving the model that inspired it?* For sure, the atomic model played a key role in Heisenberg formulation. However, the Franck-Hertz experiment itself is not a *Gedankenexperiment*. In this sense, it is not necessarily bound to interpretations leading to discrete energy levels.

Nowadays, there is a multitude of experiments that go under the Franck-Hertz suit. Even commercial devices exist, projected, built, and marketed for the sole purpose of performing the Franck-Hertz experiment. In this paper we present two cardinal experiments of those, developed by Goucher and Einsporn, respectively. They were performed at a time when the model to validate, the Bohr's atom, was still being tested. Those experiments, besides being interesting by themselves, abound of insights, more than enough with respect to the needs of the model. Nevertheless, they are not bullet-proof on critical points, as we'll see.

The Bohr's models and their subsequent transformations may work until they provide a way to grasp peculiar traits of the underlying natural phenomenon and successfully interpret experimental results. Our point is that, right now, the quantum theoretical background does not enhance the comprehension of the Franck-Hertz experiment. For comparison, we propose a rather classical electromagnetic interpretation of the phenomenon, based on a hertzian (after H. Hertz) kind of model-design.

We present historical facts, without getting much involved into historical questions. Rather, we extrapolate the hertzian train of thought enlightening it with latter-day concepts and knowledge.

On cathode rays nature

The discovery of cathode rays was followed by a diatribe about their nature. In Poincaré's words [3], "*We see [...] on cathode rays the continuation of that same quarrel that took place during the Restoration on the light beams.*" The quarrel was the same. However, about phenomena associated with cathode rays, the theories that contended for the best explanation were different. Rather than the mechanical theories by Newton and Huygens, the clash involved two electromagnetic theories: one by Lorentz and one by Maxwell.

As Poincaré aimed at a mechanistic reduction of electromagnetism, distinguishing between that kind of theories was not much relevant to him. On one hand electric phenomenology cannot leave out of consideration the matter constituting the source or the probe. To that extent, electricity and magnetism must be material phenomena. On the other hand, there are aspects in electricity that we are interested in and that have no mechanical correspondent. That's why no mechanical interpretation of electromagnetism is satisfactory. In other words, the rheologic behaviour of a viscoelastic fluid will never fully explain cathode rays propagation in a low pressure gas, nor radio waves at atmospheric pressure or in empty ether. As a concession to historical topics, it is interesting to observe that while theorists were still considering the possibility of mechanistic interpretations, experimentalists already agreed on the electric nature of cathode rays.

Those two electromagnetic theories, Lorentz's and Maxwell's, are different from each other [4]. Let's consider the latter first. Maxwell's purpose is to frame Faraday's concepts and experiences within a mathematical model. He attributes an essential significance to the shielded cage experience. That is, he assumes the electrostatic charge to be a quantity with null algebraic sum. (That assumption is known as complete electrostatic induction). Thus, as the total free charge is invariably zero, hypothesising no mathematical limitation on the absolute length of dipoles, Maxwell formally handles the electric displacement field $\mathbf{D}$ by analogy with magnetic induction $\mathbf{B}$ in Farady's Law. In facts, he also refers to field $\mathbf{D}$ as electric induction [5]. This concept allows him to add a (supposedly small) displacement current term to Ampère's equation. Such a formal amendment accounts for electromagnetic field propagation in the empty ether, and therefore it is not in contrast with Faraday's own concepts about fields. At those times, the ether was considered as a mechanical support for the propagation. It was the concept of propagation that called for the ether hypothesis: Maxwell's electromagnetic equations by themselves contain no dynamic variable.

Now about Lorentz's theory. He introduces a force to account for the mechanic effect of these fields on the matter. His expression for the ponderomotive force is inferred from electromechanical applications. However, Lorentz has to further state that electricity is inseparably coupled with elementary particles, the electrons. They are subject to a current continuity equation. The Maxwell's equations are carried over as-is into the new theory, although stressing their derivation from potentials. Hence, Lorentz reinterprets electrostatic induction, by attributing a mechanical mobility to the substantial electrical charge, and by giving conditions for its static equilibrium. Piling up of charges is not forbidden any more. Since Maxwell's mathematical field theory assumes zero total charge (a statement quite different from charge conservation) Lorentz's revision contrasts a postulate of the host mathematical theory [6]. Really, that only affects further developments of the underlying mathematics.

As for a physical interpretation, we remark that each one of both scientists formally introduces a fictitious quantity in order to mathematically handle electric phenomena. The electric displacement the former, the electron the latter. For that reason, their theories won't support mechanical explanations.

Apparently, Heinrich Hertz is the last relevant experimentalist who opposes against Lorentz's theory. Indeed, he accepts the original Maxwell's equations and shows that his own experiments with cathode rays prove them. However, his detractors find Lorentz's theory to be conceptually simpler, and they interpret H. Hertz's observations after assuming the physical existence of electrons.

We repropose in an actual vein the interpretation of his experiment on the discharge in rarefied gases, because H. Hertz himself step by step builds a model for the Maxwell-Hertz theory. For an historical account of his writing and its impact, we redirect to J. Z. Buchwald [7]. A newer publication by the same Author [8] may give further insights.

Luminescence effects in gases as elicited by electric currents

The paper by H. Hertz where cathode rays are considered as electromagnetic radiation, in accordance with Maxwell's theory is "Versuche über die Glimmentladung." [9]

It gives a clear account of experimental facts.

Our purpose in the following is to report the essential scheme of that paper with some comments.

H. Hertz asked himself three questions.

1) Is an electric discharge through low-pressure gases continuous or discontinuous?

Let's explain this question. A gas, at a pressure ranging between 1.5 and 0.01 mm Hg, is contained in a tube inside which two electrodes are sealed. These either consist of a pure high-melting metal or of an oxide coated one. Outside, they are connected through leading conductors and resistors to a battery or some other source of electric power. Experimentally, one shows that, even if the metallic circuit is not closed, current can flow through it. If the tube is thought of as a condenser filled with a dielectric mean, the flow of current is explained by Maxwell's equations, but the displacement current must be a function of time. On the other hand, if the flow of current is constant in time, then the tube operates in a non-linear manner. In such case, Maxwell's linear equations don't apply to its functioning.

H. Hertz answered question (1) on one hand by looking for alternate current (a.c.) components in the circuit, with different arrangements. On the other hand, he measured the Glimmlicht stroboscopically. That is a modification of the dielectric on the cathode side of the tube, which is observed during the time when current is flowing, and is similar in appearance to the glowing air before or during a spark breakdown of electrostatic generators. The Townsend discharge alone is a stable phenomenon up to the boosting power, where sparks shoot out. In a similar way, a tube containing a low pressure gas slowly discharges a battery, provided that it lights without breaking into pieces when the switch is closed, and that the power supplied is less than the one that starts and maintains the electric arc.

By hypothesis, a battery should supply a constant continuous current. However, the first researchers who experimented with batteries happened to draw an exceeding amount of power with respect to what the battery could deliver. Hence, they observed discontinuous glares, similar to Duddel's arc. H. Hertz increased the number of battery elements up to an open circuit potential of about 1.8 kV, and verified that the field-emission tube would not sustain possible oscillations of the circuit. In other words, he verified the absence of modulations at acoustic frequencies and up to intermediate frequencies.

This limit is imposed to him by the necessity of *transducing* the electrical signal directly, i.e. without superheterodyne [10], into mechanical vibration. Neither moving-coil or needle electrical instruments, nor common microphones are loads matching electrical vibrations directly at frequencies higher than those considered by H. Hertz.

Because of the limits imposed by measuring devices, observable frequencies might arise from emf modulation, as mentioned above, and also from arcing drop of potential for the tube (this is the modulation technique used by ancient radiotelegraph Poulsen arc transmitters.) Receiving audio frequencies through the ether would have required an exceedingly long antenna.

H. Hertz concluded that, under his experimental conditions, there was no evidence of discontinuity, i.e. pulsation. That conclusion is enforced by current use of diodes as rectifiers. Strictly speaking, that means that Maxwell's equations do not account for continuous current through the tube, nor for cathode rays, nor for the bluish light wrapped around the cathode.

In facts, when we say that the bluish light or the Glimmlicht, are electromagnetic radiations, we are extending the applicability of Maxwell's theory significantly beyond intermediate frequencies. That is, beyond the zone that H. Hertz experimentally proved free from discontinuous currents.

Is that extension correct?

That extension invalidates the linear circuits theory: we know that no metal circuit conducts violet light. Furthermore, we know that many metals show resonance lines in the violet, that is, they emit without antenna. However, if the extension of the frequency range in Maxwell's theory is acceptable, the corresponding discontinuity of current might be identified with Schottky's noise. In that sense, the definition of noise looses somewhat its absolute meaning. The *noise* becomes that part of the signal that, for whatever reason, we don't interpret.

2) Do cathode rays follow the electric lines of force?

Let's put one consideration beforehand. If H. Hertz had a standard source of cathode rays at his disposal, he would already have mentioned them in the title of this paper. That's what he did in 1892 with the paper *Űber den Durchgang der Kathodenstrahlen durch dünne Metallschichten* [11]. Rather, in 1883, the experimental difficulty was to establish what should be meant to be cathode rays, avoiding tautologies. In facts, those who discovered cathode rays did not go much further than ascribing a great deal of effects to that sole cause, without minding to distinguish between intrinsic properties and collateral effects.

Therefore, H. Hertz considered the tube as an element in the electrical circuit it belongs to, and assumed electromagnetic field equations to apply to it at steady conditions. The same hypothesis is being used today to avoid graphical methods when analysing electrical circuits: one draws the wiring diagram and replaces the diode symbol with its equivalent form. H. Hertz used linear analysis to interpolate inside the tube the measurements he took just outside it using a small magnet. He traced the lines of current of the static field, after Maxwell. He found that neither the cathode nor the anode luminescence follow those lines.

The result he found calls for two separate explanations: one for the current in the circuit and one for the cathode rays.

In primis, we have to interpret the lumped elements wiring diagram: the emf supplied is shared between the load resistance and the tube resistance at the operating conditions. The tube resistance is determined according to the static volt-ampere characteristic. In such a diagram, the figurative place where the flow tube of Maxwell's field lays is filled with the symbol of a lumped resistor, so in no place the current goes through the empty ether.

Then, there is the Glimmlicht. It is a collateral effect with respect to the use of the tube in the circuit. Indeed, thermoelectric valves that really took root make no use of it. Furthermore, the electric agent associated to the Glimmlicht in low pressure gases (and possibly to their enhanced conductivity) does not contribute to the electric current in the circuit, both visually and after Maxwell's theory, but dissipates all around. Is it possible that this agent, which is the active emission of a fed valve, behaves as an electromagnetic radiation in Maxwell's sense without being described by the circuit equations? Yes it is. The branch of electromagnetism devoted to it is known as radiotelegraphy. In the circuit, that emission accounts for small fluctuations, i.e. mathematically higher order terms. You may consider that as H. Hertz definitive answer, if you like to. However, it might not be deduced from this experiment, since a diode is no transmitter. As he himself acknowledged in 1894: "In the beginning, I thought that electric motions were too harsh and too rough to be useful"[12].

3) Do cathode rays exhibit electrostatic properties?

In the preceding question (2), H. Hertz ruled out the investigated electric agent to contribute to the mean circuit current. That does not mean that current and emission are not related to each other. In a much similar way, in question (3) H. Hertz asks himself whether cathode rays charge the matter they strike, since they consist of an electrically charged flow. He does not ask himself if cathode rays could be received, demodulated and detected as a faint current. Nor he puts up with electric wind.

Let's explain better the implications of the possible answers. In Lorentz's case, one conjectures that the neat negative charge radiates or, if you prefer a hydrodynamic analogy, that it slowly flows through space as time goes by. Then, charges may accumulate on dielectric media, according to the continuity equation, and the time integral measures the piled up ponderable or imponderable charges. In the other case, Maxwell's theory does not explain how to bring in any static electricity [13]. That's because electromagnetism formally meets the elder Coulomb's theory of *static* "action at a distance" whilst it is rather obvious that contact, rubbing, and similar ill-theorised operations play a key role in electrification. Also recall that the elder theory "at a distance" for sure didn't mean displacements of material points subject to *static applied forces* to take place instantaneously.

Nowadays we still say, about friction electrical machines, that the electricity of a sign is being conduced to ground, and we imagine that the other "tank", of less capacity, gets charged with the opposite sign. However, when both tanks have the same capacity, as e.g. in Nairne electrical machine, we consider charges of opposite sign being just separated, and we represent the pads charged at equal and opposed voltages. This non-mechanical duality of electric displacement doesn't change from the old to the new field theory.

Faraday, rather than reckoning the amount of electric charges already separated on the conductors pads, considered the polarisation of the interposed dielectric mean. In other words, he prevented the charges from arousing directly in the locations corresponding to the physical surfaces, by imposing continuity by spatial contiguity [14]. Thus far, we cannot deduce that, by the end of the process, something that wasn't there before has accumulated on the plates or in between them. That way, the results of the electrostatic experiments are preserved in the new field representation. Hence, it is the accumulation of net charge that makes the difference between the two theories, keeping in mind that Maxwell's equations provide for net charge as a boundary condition.

H. Hertz decided to consider the negative charges on the glass walls as if they were given steady conditions. He measured them after transient, on starting the first experiment of each day. He recorded the cathode ray emission by detecting its fluorescence. More precisely, he detected the fluorescent signal of the glass surface on the bottom of the tube, which was completely shielded from the electrodes.

His generator incorporated a Ruhmkorff coil, so current was *alternate*. H. Hertz was forced to the choice of that generator, and therefore he had to check that Maxwell's term for the displacement current, whatever it physically means, didn't impair cathode rays. Basing on his own experiments, he excluded that the glass, besides fluorescing, also got charged. More precisely, he wrote that near to the cathode, upstream of the shielding, the glass envelope got at a negative potential in a durable way. He didn't relate that fact directly with cathode radiation. He also observed that, by applying an additional electrostatic field, the breakdown threshold was lowered, and neither that he considered to be a first order effect.

The missing detection of the alternate current has been puzzling the interpreters of his experiment subsequent to himself.

Heating the cathode was an innovative technique at the time. As H. Hertz doesn't mention it, we presume he used no hot-cathode device in this experiment.

We are suggesting that H. Hertz's diode didn't detect alternate current because cold-cathode diodes do not rectify it [27].

His negative answer to the third question is remarkable, but for the time being, we just like to pinpoint consequences of H. Hertz's (and J. Maxwell's) choice that are under everybody's nose.

The superposition principle applies to (homogeneous) solutions of wave equations, not to a flow of charge. For the same reason, frequency spectra analysis can characterise waves, not flow of charge. A phenomenology requiring an extensive development of the flow of charge theory would not have lead to telecommunication technology as we know it today.

We don't mean that hertzian experiments were aiming at telecommunications development, as the latter technology didn't exist as a project, before H. Hertz. His discovery is different: to whom who stops considering electromagnetic induction as just a property of the magnetic flow, which induces an emf in the relevant circuit [15], electromagnetic *far-field* theory may appear as a new (linear) physical theory. Otherwise, it is just bare mathematics, without the multiplicity of electrical displays on the matter [16]. In his own words [12]: "It was the distance at which I could perceive the action, getting larger and larger, what aroused my utter astonishment. Until then I was used to see electric forces diminishing with Newton's law, i.e. rapidly vanishing as distance increased."

The electric measurement of excitation and ionisation potential of gases

Besides the so-called silent electric discharge, luminous emission from gases can be obtained by heating or with sparks. As techniques became finer and finer, an empirical rule for emission was stated as

$$1234 = \text{wavelength} \times \text{voltagedrop (nmV)} \qquad (1)$$

Indeed, without a systematic approach, the phenomenology looked more puzzling. On one hand, the experiments with enough gas pressure to make the Glimmlicht visible agreed that there should be a relation between the electrical parameters of the gas valves and its (cold) emission spectrum. This very fact was expressed by the *simple relation* written above. On the other hand, the electrical functioning of the valves themselves satisfied no linear relationship.

Truly, electric ionisation experiments were sophisticated ones. Furthermore, at those times it was believed that natural laws, being concerned with material bodies as sensible objects, could eventually be expressed as dynamical laws. (That is, e.g., after, reducing phenomena from a thermodynamic description to a statistical mechanics formulation.)

As there is no easy mechanical way to lead a gas into emitting light, we may say that valves of the De Forest type, i.e. triodes, tetrodes, etc., were used because they were supposed to emit electronic particles endowed with mass [17]. The experiments were devised in order to accelerate those particles by applying an electrostatic potential, measuring the values at which the impulse would have been transferred to an atomic gas by means of inelastic conservative collisions. As it is still currently being taught, at the potentials where inelastic collisions take place an electron-bullet wouldn't have enough kinetic energy to hit the anode. At the same time, after a gas atom target has absorbed its impulse, it would transfer it on a higher energy Coulombian/Newtonian orbit of its optical electron.

Those measurements were not quite mechanical, but they rather involved electric quantities – the small variation in the continuous anode current. Nevertheless, researchers could readily imagine electrons escaping the cathode material toward the interspace. They imagined the electrons and/or the positive ions produced in the collisions would have been gathered on the anode. To wit, they thought of the electrical feeding essentially as a mean for boiling electrons off the cathode.

The researchers who carried out those experiments deemed them *fundamental,* that is oriented toward understanding nature at a most basic level, in contrast to other contributions to electronics, more aimed at applications and technology.

That way, H. Hertz's basic idea that a cold-cathode diode fed with power from electric batteries behaves as an electrical lamp[1], and that its emission

[1] See T. A. Edison 1883, for thermoionic type of lamps.

could, in first approximation, be described by Maxwell's equations, seemed to be missing an essential aspect of electrical phenomena.

Stemming from the lack of familiarity with bare electrical explanations, Bohr and Sommerfeld's atomic models aim at *rationalising* relation (1) above, i.e. bringing it down to mechanics. The experiments, controlling temperature, purity and concentration of gases, and also polarisation and oxidation of electrodes, etceteras, aim at verifying the *numerical correspondence* between the frequency values computed after law (1) of the model and the optical spectra recorded directly.

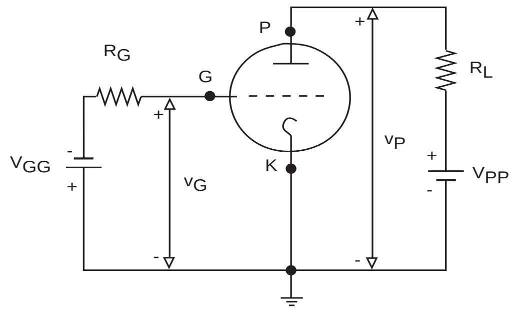
With respect to that verification, Franck and Einsporn expressed themselves with words like the following [18]. "*We ask ourselves why the lines corresponding to the transitions 1.5S – mp1 (wave length 2656 Å) and 1.5S – mp2 (wave length 2270 Å) of mercury vapour, that should stay in some easily accessible ultraviolet zone, have never been observed up to date in neither emission nor absorption optical spectroscopy. In particular, our measurements suggest that the line corresponding to 1.5S – mp2, that we clearly see on our graph as a sudden increase in current at about 5.43V, should be allowed.*"

Since 1926, the Franck-Hertz experiment has been dealt with using the mathematics of self-consistent field theory [19]. If that is its explanation, the Franck-Hertz experiment ceases to be *fundamental* in that it isolates a distinct natural phenomenon and lays it bare for comprehension by a physical theory. It may be considered a fundamental experiment for some other reason, such as, e.g., supporting the aforementioned mathematical theory. The point is that its conceptual binding to quantum mechanics becomes somewhat loose [20]. It appears as if one could not deduce any failure of the probabilistic quantum theory from experimental results of experiments like this.

Now observe that quantum mechanics assumes a unique "mechanical equivalent of electricity." A concept that Lord Kelvin traces back to Aepinus [21]. It is manifest in the Lorentz force, which represents a sort of electromechanical transduction. That law cannot be easily extended from atomic behaviour to the efficiency of a working engine. Anyway, if it held true for electrical circuits, then impedance matching would be an option even when designing high frequency transmission lines. On the opposite, experience suggests that a significant mismatch is not compatible with gain and high power levels already at higher audio frequencies.

From a modern point of view, the H. Hertz experiment described above can be seen as an unusual diode application. In facts, diodes are used as rectifiers more often than not. Likewise, experiments of the Franck-Hertz type can be considered unusual applications of triodes and tetrods. Are they fundamental only because they can be explained theoretically? Then, one may ask, why doesn't the underlying theory rely on widespread applications of those valves?

Consider Maxwell-Hertz theory. Although it is not founded on widespread applications of valves, in practice it has been supporting their implementation ever since. Perhaps unusual applications are more difficult to interpret within that theory simply because the experimental design is just not aimed at that.



P is the plate
G is the grid
K is the cathode
V_{GG} is the grid supply voltage
R_G is the grid static resistance, if this electrode is drawing a current i_G
V_{PP} is the plate-to-cathode voltage bias
R_L is the load resistance
if v_G is the input potential, i_P is the output current
Cathode-heating circuitry is omitted

Figure 1: A basic grounded-cathode circuit

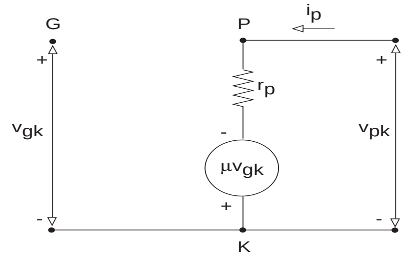
F. S. Goucher and the Barkhausen-Kurz generator

Goucher [22] has been one of the researchers who contributed methodological improvements to the original Franck-Hertz experiment. With respect to H. Hertz time, feeding, thermostatation, and vacuum technique have improved. The purity of the mercury certainly has a higher standard. Most importantly, there is one more electrode in the tube: a grid (that Goucher called *gauze*). That's an important innovation, as the third electrode can modulate the electromagnetic response of the valve.

Better on that concept. H. Hertz measured only one curve of current corresponding to potential drops across the diode, given load and battery. In the triode, the non-linear relation F(V, I) depends on two more parameters, as one may vary potential and current through the third electrode too.

In electronics, the superior versatility of that component leaded to the standardisation of a few families, depending on applications. Let's examine two usual applications of vacuum tubes.

As a first example, consider high fidelity amplification of weak electromagnetic signals at audio frequencies. We restrict to the essential, omitting even the transduction step into audible sound. Fig. 1 shows the basic schema of a triode configured as a common-cathode wide band amplifier, with grid and



$r_p \equiv \left(\frac{\Delta v_P}{\Delta i_P}\right)_{V_G}$ is the plate resistance
$\mu \equiv -\left(\frac{\Delta v_P}{\Delta v_G}\right)_{I_P}$ is the amplification factor
$v_{gk} = v_G + V_{GG} = \Delta v_G$ is the input voltage drop
$v_{pk} = v_P + V_{PP} = \Delta v_P$ is the output signal
across load resistance R_L, i.e. $v_{pk} = -\frac{\mu v_{kg} R_L}{R_L + v_P}$
Configuration is grounded-cathode. Quiescent point
values on a static plate characteristic
$V_{GG} = const, I_P = I_P(V_{PP})$ are not stressed

Figure 2: Thevenin's linear model for the updated range over which μ and r_p are substantially constant.

plate supply batteries.

Amplification being untuned, the output signal, i.e. the plate current on an external resistive load, at the operating conditions is the linearly amplified input signal, i.e. the variation of the grid potential. Then, the circuit can be represented as a two-port network having a lumped output impedance in series with a generator, equal to the open circuit voltage.

Fig. 2 shows the schematic voltage-source model where supply batteries are no more included, as usual.

As a second example let's consider the generation of a carrier for radio broadcasting (without radiation step "coupling" to the ether channel). The basic scheme of Fig. 1 for the triode may be kept valid if we substitute a parallel circuit **LC** for the resistive load $\mathbf{R_L}$. The new element plays the role of a passband filter at the carrier frequency. However, the simple scheme in Fig. 2 doesn't apply any more, because now amplification is tuned. Furthemore, the input has to be obtained feeding back part of the output. If the feeding back keeps the correct input-output phase relationship an oscillation starts and builds up as the biased amplifier is matched at the correct frequency and tracks it. Technical improvements allow to get a steady carrier with low harmonic content, low levels of sideband noise and low thermal drift rate. At variance to the first example, the output is typically on/off. It is not linear, nor it can be obtained from linear amplification by a perturbative approach.

The quirk in using a triode as in Franck-Hertz experiments doesn't lay in

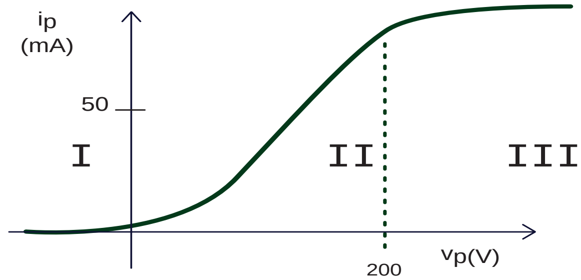


Figure 3: Shape of a volt-ampere diod's characteristic for a high-vacuum tube with pure tungsten cathode at T $\simeq$ 2200 K

any dissimilarity from the scheme in Fig. 1, but rather in its atypical circuitry, with respect to usual applications.

Really, Goucher used the third electrode to control the valve, but he didn't bother about "tube characteristics." The reason is that he was interpreting his observations after hypothesising a slow flow of particles. By that hypothesis, the investigation became concerned with the distribution of velocities of those particles. The non-linearity of the characteristics was considered "experimentally uninfluential" until it didn't increase the dispersion around the mean value of that distribution.

Now, let's substitute those thermo-emitted particles accelerated via an applied d.p., which ionise the gas because of collisions, with the alternative picture. Let's say that, since the casing and contents behave as a triode, the signal distortion arising because of the non-linear characteristics explains the presence of an output without external input.

We show that Fig. 3 of Goucher's paper (which we number as Fig. 4) is a characteristic curve of that valve, and that its non-linearity justifies the onset of persistent autogenous oscillations of his thermoelectronic tube at the expenses of the plate feeding power.

We like to start by telling about characteristics of vacuum tubes. As we said above, about H. Hertz experiment, if we consider a diode as a planar equipotential-surfaces condenser, then, according to electrostatics, the potential between the electrodes is a linear function of their distance, and to a good approximation there is no current flow. In disagreement with electrostatics, a thermoelectronic diode can conduct, and, although to a far lesser extent, also a cold-cathode diode can. The relation between the continuous current through it and the potential drop, its static characteristic, is non-linear.

As shown in Fig. 3, qualitatively, we distinguish three ranges of a commercial thermoelectronic diode's characteristic. There is a lower saturation range (I) at negative potential, where the diode approximately doesn't conduct. There is an upper saturation range (III), where the maximal current essentially depends on the cathode's hot filament supply. Then, there is an intermediate range (II) where the relation between $\mathbf{i_P}$ and $\mathbf{v_P}$ is considered to depend on the surface conditions of the cathode, on the way it's feeded, on the material of the electrodes, on their geometry, and on the residual gases in the tube. The trend may seem quadratic, but probably it is even more complicated.

In the following few paragraphs, we describe the curve for a vacuum tube having three electrodes.

We already mentioned that the grid control introduces a further parameterisation of every isothermal characteristic function. In facts, the common cathode triode may be considered as composed of two interlaced diodes: an input diode, consisting of the cathode and the grid, and an output one, consisting of the same cathode and the anode.

Consider the static parameters $v_{\mathbf{G}}$, $v_{\mathbf{P}}$, $i_{\mathbf{G}}$ and $i_{\mathbf{P}}$ of the triode, where **G** (for grid) indexes the values pertaining to the input diode while **P** (for plate) those of the output one. By a careful design, the amplification can be made quite linear, with an amplification factor between 10^2 and 10^4 at the clamps, in a certain range of the static parameters. In that range, the parameterisation of the static characteristic is a repetition of the same curve at different offsets. To wit, a given output characteristic ($v_{\mathbf{P}}$, $i_{\mathbf{P}}$) generates regularly repeated graphs for a set of fixed $v_{\mathbf{G}}$'s that differ from one another by a constant amount.

We have $v_{\mathbf{G}} = v_{\mathbf{G}}(i_{\mathbf{G}})$, and the input diode characteristic ($v_{\mathbf{G}}$, $i_{\mathbf{G}}$) is nonlinear as a whole. That's why amplification without distortion typically implies $i_{\mathbf{G}} \sim 0$, that is this diode is cutoff. In turn, this means that the grid's potential has to be negative w.r.t. the cathode. Hence, we see that the purpose of using a positive grid potential to accelerate electrons may become incompatible with a nicely linear response of the triode. This terminates the digression about tube's characteristics.

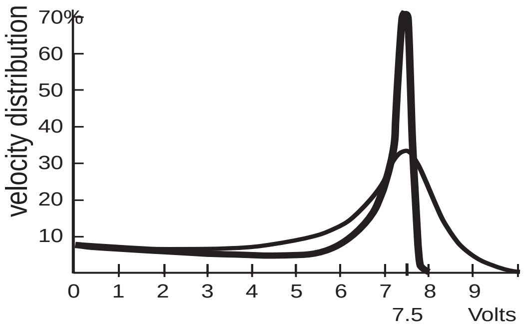
Back to the aforementioned Goucher's paper. The stated aim of Fig. 4 is to show that the triode being used is more suitable for measuring ionisation potentials than Pawlow's one. So we may compare two performances and check what's the technical improvement.

Goucher's tube featured an indirectly heated pure metal cathode (Pt). The vacuum obtained from hydrogen was better than 0.005mm Hg (which is still about 10^3 times worse than high vacuum in 1949.) Measurements were carried out maintaining the grid potential $v_{\mathbf{G}}$ at +7.5V, varying the static grid-plate decelerating potential $v_{\mathbf{GP}}$ between 0 and 10V point by point, and registering the corresponding plate electrical current by means of an auxiliary field electrometer when stationary conditions were attained.

In Fig. 4, on the ordinate axis he plotted the calculated slope of the experimentally measured $i_{\mathbf{P}}$ as a velocity distribution. The calibration was the percentage of the graph area, between 0% and 70%. On the abscissa, he plotted the values of $v_{\mathbf{GP}}$ between 0 and 10V.

Since $v_{\mathbf{PG}} = v_{\mathbf{P}} - v_{\mathbf{G}}$, and $v_{\mathbf{G}} = 7.5$V,
$v_{\mathbf{PG}} = 0$ implies $v_{\mathbf{P}} = 7.5$V
$v_{\mathbf{PG}} = -10$ implies $v_{\mathbf{P}} = -2.5$V.

On the other hand, we have



Tracing according to Goucher's Fig. 3 of [22]

Figure 4: Goucher's and Pawlow's experiments

$$\left(\frac{\partial \mathrm{i}_P}{\partial v_{PG}}\right)_{\mathrm{v}_G} = \left(\frac{\partial \mathrm{i}_P}{\partial \mathrm{v}_P}\right)_{\mathrm{v}_G} = \mathrm{g}'_P = \frac{1}{\mathrm{r}'_P} \tag{2}$$

Therefore, the graph he plotted may also show a plate static differential conductance as a function of the plate potential. The apex indicates that, if amplification is not linear, conductance differs from that one for small swings around the chosen working condition. We'll now argue that Goucher's project aimed at enhancing the non-linear functioning.

When the common cathode triode is used as a voltage amplifier, that is it exploits the linear characteristic range, it exhibits a high plate resistance, which contributes to the remarkable value of the linear gain factor $\mu \propto r_P$.

That might hold for both Goucher and Pawlow tubes, up to about half of the abscissa range. Thereafter $\mathrm{v}_{\mathbf{P}}$ tends toward 0, while the input diode is not cutoff. That implies $\mathbf{i_G} > 0$: Goucher doesn't say it for this triode, but for the one on page 570 of his paper. This current flows in the input diode, generating a voltage drop, and hence it supplies to the output an additional voltage "in phase" with $\mathbf{v_P}$.

According to commercial data sheets, the positively polarised grid draws more and more current as the plate potential tends toward zero.In the same conditions, according to Fig. 4, Goucher's tube conductance climbs showing a much narrower "gaussian" peak than Pawlow's. Moreover, it grows in spite of there being no external user requiring the current to increase. Finally, it abruptly hits the abscissa axis with a distinctively not horizontal slope. For the remaining 2V, only the slow descent of Pawlow's tube is reported in Fig. 4. Perhaps Goucher got negative conductance?

As far as the area under the graph is concerned, a very steep tract with negative conductance wouldn't contribute much, and hence any correction bears no importance. However, for the sake of the triode electromagnetic response, to exhibit a negative conductance implies an instability of amplification. To be precise, for those bias conditions the triode performance looks like that of a generator. In facts, the Barkhausen-Kurz generator for U.H.F. is connected and polarised nearly the same way [23]. Obviously, an oscillator circuit usually contains also filters and provides for a matching at the desired frequency of oscillation. Goucher's circuit consisted of just the tube. That notwithstanding, according to this interpretation, it oscillated.

So, this is the big difference between the diodes that H. Hertz used to work with and these fine workmanship pure metal cathode triodes. The former couldn't generate any radiotelegraphic carrier. The latter typically resonate in certain frequency ranges. Indeed, between 1928 and 1929 commercial triodes and tetrods have been substituted with pentods for linear amplifiers, or they have been cascode configured.

As a further look inside the technological development trend of those experiments, we also report an improvement suggested by G. Hertz for noble gas, helium-neon or metal vapour, triodes: "*The heated cathode [...], with a drop of barium oxide on its surface, is at about half a millimetre from the close-meshed grid. [...] The space between the grid and the plate is an enclosed metallic cavity, except for a small slit [...]*" [24].

We conclude that Goucher's efforts were directed toward improving the grid-plate coupling of his tube, in order to increase its positive feedback and quality factor, by keeping losses as low as possible.

E. Einsporn and the voltage controlled oscillator

Einsporn [25], one of Franck's co-workers, considered a common-cathode configured *thermoionic* tube of four electrodes.

He made two different series of measurements: in the first one, he measured mercury excitation potentials, using the tetrod as a triode. In the second series, he measured ionisation potentials, for comparison with Goucher, using the tetrod as a diode.

In the first series, the Author applied the "accelerating" positive potential between the cathode and the second grid, that is the one near to the plate. Now, when the first grid is earthed, the tetrod works as a triode. Furthermore, as the amplification gain is related to the ratio between the geometrical plate-to-grid and grid-to-cathode distances, we may consider it small, except at those working conditions where the input couples with the output.

During the experiments, the grid potential was set at a chosen value between 0 and 25V, whilst the plate one was held slightly positive w.r.t. the grid (max. 1V). The corresponding measure of current was taken. The whole procedure was to be repeated for each value of the grid potential.

The curve reported in his Fig. 2 and redrawn in our Fig. 5 to interpolate his data for the plate current as a function of the grid potential, is not a mutual characteristic in the prevailing sense of this term. In facts, it consists of points from a set of data that we can regard as plate characteristics. Now, if the whole

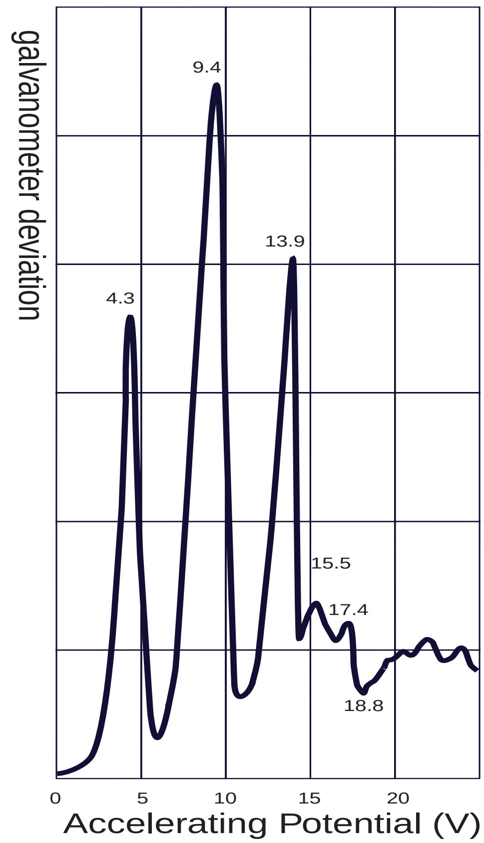


Figure 5: Tracing of Fig. 3 according to Einsporn [25]

valve, i.e. outer casing, electrodes, wiring and gas, only amplified more or less linearly the static input potential in the considered biasing range, then the slope of that curve should exhibit no irregular climbing, or at least it shouldn't change sign. Instead, Einsporn himself calculated interpolations as if the curve had several narrow local maxima. These are well distinguished at the grid potential values A, 2A, 3A and their products with another potential B. As usual, he related those peaks to the UV spectrum of the gas inside the casing, by means of the simple law (1) rewritten as $eV = h\nu$. In facts, he believed the UV radiation to arise owing to jumps between discrete energy levels, which he deemed to exist and to be gas' property.

Such picture originates on the sole basis of the electric measurements. The low-pressure gas is inside the tube, and departures from linearity of the mean anodic current as a function of the potentials are ascribed to the gas only. If that were true, then it should be possible to schematically decompose the circuit into two non-interacting parts: a triode that works as a linear amplifier and a variable resistance, say an external RCL load having complex impedance. The hypothesis is that the low pressure gas in the classical electromagnetic theory can be schematised as if it behaved linearly in the circuit. That is to say, we attribute to the gas an attenuation constant equal to the real coefficient of the impedance, and a phase constant equal to the imaginary coefficient [26]. If the circuit is supposed to resonate at the cascaded RCL mode of the gas, the current maximum (achieved at the expenses of the plate battery) corresponds to the load driven to resonance.

If the circuit behaved like an amplifier plus a lumped RCL load, as measured from the signal detected with a moving-coil mirror galvanometer, the input circuit of the amplifying triode should provide for a frequency sweep to drive the gas RCL to resonance. On the contrary, Einsporn's input supplied static potential differences. In order to interpret the experiment according to Einsporn, we should substitute the amplifier with a fluorescence spectrometer.

Analysing Goucher's Fig. 3 (our Fig. 4 above), we just saw that a tube devoid of gas may perform as a generator at well chosen operating conditions. If the frequency of the generator were a linear function of the grid potential, then there would be no need to project VCOs (voltage-controlled oscillators.) A simple potential-to-frequency conversion formula of the kind of law (1) would already fit the macroscopic triode object. In facts, characteristic curves are already non-linear at low frequencies, and at high frequencies the lumped parameter wiring diagrams fail altogether.

Fortunately, valves of the kind used by Einsporn, containing low pressure mercury vapours, are not really uncommon products. They have been implemented in various ways during the last decades. They are known in the literature with the name of tiratron. They are used as switches in circuits, as alternatives to the ignitron [27]. When the valve is on, it tends to radiate like a resonator rather than like a linear antenna. According to the present interpretation of the Maxwell-Hertz theory, the metal making up the body of the cathode is the matter being directly electrically strained. It becomes hot. It becomes saturated by the power it cannot convert into emission, and radiates everything else. After a transient, the metallic surface of the catode is *electrically* coupled to anything that can resonate in the valve, in particular to the mercury vapours.

Visually, a bluish emission surrounds the cathode, and all other luminescence effects which are more easily spectroscopically analysed, take place in the tube [28]. Truly, we have included the globally non-linear performance of the valve in the term "saturation". Nevertheless, that doesn't mean one cannot measure "intermodulation products" in lower frequency ranges by means of a suitable analyser. Nor does it mean that linear waves theory cannot be profitably used to interpret those measurements. The only prohibition involves the kind of spectral analysis implied by law (1). Such prohibition is prominently related to the paradoxes arising from the subdivision of the continuum into discrete parts, and it is purely of mathematical nature.

The second series of measures in Einsporn's paper was intended for comparison to the new ionisation potentials that Goucher had been measuring meanwhile. They have been carried out on the tetrod with corrections for taking into account the photoelectric effect. As stated in theoretical prescriptions, a strongly negative cutoff potential has been applied to the plate, or, with the aforementioned corrections, to the screen-grid.

The current vs. potential curve becomes similar to that of a diode, exhibiting moderate climbing at the potentials where ionisation is expected. That curve indicates it's impossible for the triode in those operating conditions to oscillate (off-condition). It does not mean that its behaviour becomes linear.

To summarise, the original Franck-Hertz experiment, rather than quantitatively confirming a simple law, suggests that physical transduction of electrical, thermal or acoustical quantities in radiative phenomena is a non-linear performance.

Not that the alternative suggested here, to describe the electric interaction between a biased triod and the gas therein as a modulation of electromagnetic radiation due to electrical coupling, is easier or more convenient to deal with. Nevertheless, if the cavity inside triodes could be made selective enough, as wished by many of the authors mentioned above, then the modulation could be simplified by applying sum and product trigonometric formulas, and some additional insight into frequency relationships could be gained by comparison with experiments.

Conclusions

On reinterpreting those fundamental experiments, the weakness of the current concepts about telecommunication theory seems to be that it is not based on a signal theory, by which we mean an enhanced interpretation of Maxwell's equations. Rather, it's based on many communications and information theories, accompanied with Lorentz's interpretation of electromagnetic fields.

We have reported the mentioned paper by H. Hertz on the Glimmlicht. We have interpreted it with the hindsight given by current advancements in the telecommunication field. H. Hertz's experiment appears to adhere closely to that interpretation based on Maxwell's equations. The reason is precisely that the Author perceived the validation of Maxwell's equations as a task separate from, and prevalent on, the explanation of specific transduction mechanisms. That approach was a good start for founding a detected-signal theory. However, the pivotal beliefs around which the research was wandering at the time are the same for all the Authors we mentioned. They concern the discrete nature of matter and the dynamical model of electromagnetism.

Are those beliefs still current?

In practice, the molecular model of the matter has always been agreed upon universally. Except for E. Mach, who criticised it basing on his own results in optoacoustic experiments. He didn't accept it because he couldn't figure out just how statistical movements of particles would propagate as nearly monochromatic waves [29] or elicit them.

After H. Hertz's time, the relationships among the world out there, the sensitive experience, and its interpretation, have been the subjects of much writings and discussions. Today, a few people believe that Bohr's atom is a faithful description of something that really exists in the physical world. Most consider it a useful intuitive guide. A model, that is.

In this respect, atomism in general may be thought of as a linear model of those relationships with the external world. Working on the resulting representation, we can take advantage of its simplifications. However, we'll also be hindered by its limitations: no further approximation can be easily obtained by introducing small perturbations. In facts, it is not possible to use a linear model to represent an interaction, be it dynamic, energetic or whatever.

As far as a purely mechanical explanation of electromagnetism is concerned, we know that Maxwell himself discarded it. After the success story of telecommunications, if we accept that electromagnetism just explains itself, we don't see any special reason to model the current by analogy with convective movement. Moreover, as we avoided the previous analogy, we should have no reason to bind the charge to a mechanical entity either.

In order to sketch a detected-signal theory, let's reconsider the diode for a moment. By varying the potential difference between the electrodes, the valve, as it rectifies the current, allows its detection. If we don't interpret that current as a flow of particles, we may consider it as just the way a diode detects varying potentials. In radiotechniques, people talk of rectification of electromagnetic oscillations: of a signal, that is.

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